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# Adaptive Refinement and Coarsening for Virtual Surgical Environments

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## Abstract

Adaptive refinement & coarsening is a technique being used to model human tissues for use in virtual surgical environments. The technique uses elements of finite element analysis and physically based modelling and provides a dramatic reduction in computational complexity. An example simulation shows that the adaptive scheme achieves interactive rates with complex deformable and fracturable models.

## 1. Introduction

The use of interactive computer graphics to represent complex biological systems has proven to be beneficial in a variety of areas including surgical path planning, analysis of biological function and surgical simulation and training [3], [5], [6], [10]. Our objective is to develop a virtual surgical environment by creating realistic, manipulable models of the anatomy and to provide feedback and control similar to the actual environment. In particular, retraction, dissection, cauterisation and excision of organs needs to be performed with sufficient realism to develop the necessary skills to perform surgery.

This paper presents a framework that addresses these issues by providing a number of graphical models suitable for surgical simulation, as well as describing techniques designed to reduce computational complexity and provide interactive response. We have developed a novel interactive surgical simulation environment by integrating a variety of techniques in physically based modelling [7], [9], [11], [13] and finite element analysis [1], [2].

## II. The Animation System

We have chosen a method based on the model proposed by Norton et al [9] as the basis for our simulation environment. This model provides a method for dynamically modelling breakage as a result of stress accumulating and being released as the fracture progresses. Furthermore, this technique does not use the elaborate finite element techniques that, although more accurate, are computationally expensive and prevent real-time performance.

### A. Physical Attributes

The model consists of a mesh or graph:

$$N(t) = \{n_i(t), b_{ij}(t)\}$$

where  $\{n_i(t)\}$  are the nodes (vertices) of the graph;  $\{b_{ij}(t)\}$  are the bonds (edges) of the graph; and  $t$  represents time.

A number of time-dependent parameters are associated with the nodes and bonds so a dynamic model can be produced. Each node,  $n_i(t)$ , has three parameters associated with it:

- ▮ Mass  $m_i$
- ▮ Position  $R_i(t)$ , a 2- or 3-vector
- ▮ Velocity  $V_i(t)$ , a 2- or 3-vector

Depending on the object being modelled additional parameters may be associated with nodes e.g. colour, texture map coordinates and temperature.

Each bond  $b_{ij}$  connects node  $n_i$  with node  $n_j$ . Only one bond is associated with any given pair of nodes  $(n_i, n_j)$ . A force  $F_{ij}(t)$  is associated with each bond.

This force is derived from the physical model used. For example, a linear spring model can be used to model objects with linear elastic response. More complex force functions may include plastic and visco-elastic behaviour [12].

### B. Geometry

A microgeometry based on a cubic lattice has been chosen as the basic building block for constructing larger three-dimensional objects (two-dimensional objects use a square)<sup>1</sup>. One such cube is illustrated in Figure 1. The diagonal bonds of the cube add rigidity and make it structurally stable. The cube of Figure 1a has four diagonals and although these are not sufficient to constrain all degrees of freedom, the more stable configuration of Figure 1b shows little

<sup>1</sup> A cubic lattice has been chosen because of the simplicity with which objects can be tessellated. In particular, we intend on using MRI datasets to build the models and these are represented by a 'cubic' dataset.

difference in behaviour under simulation [9]. Multiple cubes are joined to form a lattice that approximates the desired shape.

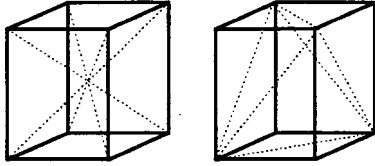


Figure 1: a) Four internal diagonals used to provide stability to the cube. b) The more complex cube with six face diagonals shows only minor differences in behaviour.

A coarse lattice will result in spatial aliasing, and finer lattices will result in immense data sets. Norton et al [9] suggested distorting the lattice elements so that they are not precise cubes. This enabled them to approximate nonrectilinear surfaces more accurately with a relatively coarse lattice. Our method allows the cubic lattice to be non-uniform in size (see Figure 2). This allows us to refine the model in regions where the coarser approximation is not suitable. There are certain constraints imposed on this size variation but the grid effects are easily masked without distorting the cubes in the lattice.

#### C. Dynamics

Now that a geometric model has been realised, Newtonian mechanics can be used to compute the evolution of such a system in time. By integrating Newton's second law,  $F = ma$ , all the masses (nodes) in the model can be accelerated according to the total forces acting on them. In the current environment the total force  $F_i$  includes gravity, internal bonds, collisions and frictional forces. Collision forces are approximated by a penalty method described in [7].

#### D. Fracture

An accurate model of the fracture process requires a high degree of computational complexity and is not suitable for real-time simulation. Since the main reason for breakage in a surgical simulation environment is due to cutting of the organs, a simplified model is used to provide an adequate response.

The breakage model used in our environment defines a threshold such that when the force applied to a bond is greater than the threshold the bond breaks. It is unlikely that typical surgical procedures would result in a compressive fracture. Therefore, this breakage model only causes a bond to break in tension, not in compression.

This breakage model, with individual bonds breaking when sufficiently distorted, is not adequate. If only a few bonds in a given cell break, this cell will no longer be structurally stable. The end result will be strings of flexible material after fracture. The introduction of a cell based breakage model solves this problem. A cell is a set of nodes and associated bonds; a cell can be thought of as the basic structural entity which disintegrates after breakage. For the cubic lattice the cube and its associated nodes and bonds will be a cell.

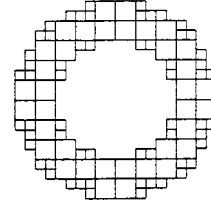


Figure 2: The adaptive approximation of the object

Whenever any single bond is broken, all cells associated with that bond are said to be broken. Conversely, if all cells containing a bond are broken, we cause that bond to break as well. The result of this cell based breakage is that the fragmentation occurs in cellular units and the structure maintains its stability.

Up to this point the breakage model we used is identical to that of Norton et al [9]. We have extended this model by specifying that breakage of a cell can only occur if that cell's refinement is at some predefined maximum value. This additional constraint ensures that breakage occurs at the smallest cellular level and is a direct consequence of the adaptive refinement and coarsening technique.

#### E. Collisions

Extensive research in collision detection has been pursued in the fields of CAD/CAM and robotics [2], [7]. Some of these algorithms have more generality, at a higher cost, than is necessary for surgical simulation. The environment we are using supports only node based collision detection between impenetrable objects and the physically based deformable models discussed. This is clearly inadequate and work is in progress to integrate some of the more advanced collision detection algorithms with the adaptive refinement system we are developing. However, even this simple collision detection system produces pleasing results when cutting the deformable models with an impenetrable "scalpel" object.

### III. Adaptive Refinement and Coarsening

Using the dynamic modelling technique described to provide an accurate representation of human organs is too slow for interactive performance. The adaptive refinement and coarsening method has been

developed to overcome this through careful consideration of the properties of our surgical simulation environment.

Using the normal modelling method a large amount of computational power is wasted in regions of the object's mesh which are not undergoing any deformation. Using adaptive refinement and coarsening the mesh used to simulate the dynamics of the object has fine structure in areas of greatest distortion and fracture. Additionally, the areas where this distortion will occur are not known a priori so the response of the model to deformation and fracture dictates the refinement and coarsening as the simulation progresses.

#### A. Adaptive Refinement and Coarsening: Implementation

There are four aspects to the implementation of adaptive refinement and coarsening:

1. the strategy for mesh refinement.
2. the criteria for refinement and coarsening.
3. the attributes of new nodes and cells created by refinement.
4. the attributes of the nodes and cells which are created by coarsening.

##### 1. The mesh refinement strategy

A number of mesh adaptation strategies have been proposed for use in finite element analysis [8]. In this system an 'h-type' adaptation is used, where cells are selectively refined in parts of the mesh during the evolution of the simulation. Additionally, the refined cells are coarsened when they are no longer needed, so that computational power is not wasted on those parts of the mesh that are no longer undergoing deformation. The addition of the coarsening strategy was motivated by the way certain parts of the mesh 'freeze', so that a coarse mesh captures the behaviour effectively.

In the h-method a single quadrilateral element may be refined or split into equal-sized smaller elements, or the refined elements may be coarsened or combined into a single element. We will refer to the original unrefined cell as the 'parent' and the refined cells as the 'siblings'. Each set of siblings results in the addition of one 'generation' where the original cells of the model are generation zero.

##### 2. Criteria for Refinement and Coarsening

To establish criteria for refinement and coarsening we considered the properties of our animation environment and selected three goals:

1. Maintaining interactive response
2. Realistic physical interaction
3. Realistic visualisation

Consideration of these goals resulted in the following adaptation criteria:

¶ Nearing-fracture: a measure of how close an edge is to breaking point.

¶ Local distortion: a measure of the angular distortion between neighbouring cells

The first criterion refines the model prior to fracture and results in refinement of edges under high stress. The second maintains the visual appearance of the object by refining areas of rapid change in stress. Additional parameters are used to prevent the oscillation of refinement and coarsening of a cell by adding hysteresis to these criteria e.g. a cell must be selected for refinement more than once for refinement to occur.

##### 3. The Process of Refinement & Coarsening

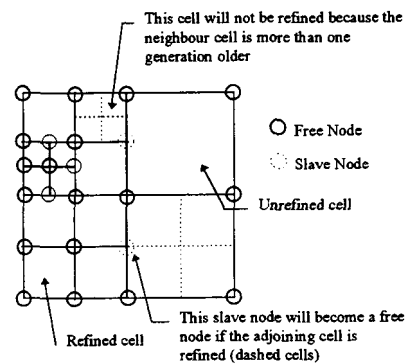


Figure 3: The Process of refinement

During refinement and coarsening, cells are either created or destroyed. For the model to remain consistent in its motion, mass, velocity and position must be recalculated for the effected cells. A two-dimensional description of the process of refinement and coarsening will be used to explain the calculation of these new conditions. In the two dimensional case squares are used as the basic cellular unit. The extension to three dimensions is trivial.

##### a)Refinement:

During refinement, four new equal sized sibling cells are generated. The new nodes generated from this process may be of two types:

- ¶ free: a node is free if all the cells it is associated with are of the same generation
- ¶ slave: a node is a slave if it is not free

Free nodes have initial conditions averaged from the parent cell and are assigned a mass equivalent to the portion of the original cell they represent. Slave nodes are fixed at the average position of the 'master' nodes associated with the edge bounding the two cells that are of different generations.

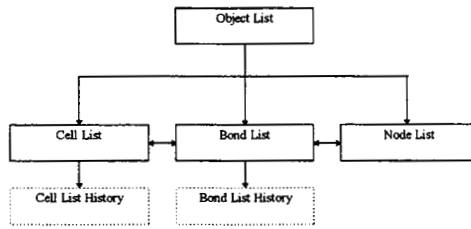


Figure 4: Data structures and their interdependencies. The two history lists are used to maintain the 'family tree'.

During the course of a simulation, a slave node may be converted to a free node if the unrefined neighbour cell is refined.

Although it would be possible for a refined cell to be selected for refinement by the adaptation criteria, this is not always desirable. When a cell is refined next to an unrefined cell a slave node is created on the shared edge. This slave node provides no additional accuracy to the dynamics of the model and continuing refinement of the refined cell will simply result in many more slave nodes with little effect on the dynamics. For this reason, cells are only refined when the surrounding cells are within one generation; this prevents the creation of unnecessary slave nodes. Figure 3 illustrates the process of refinement.

#### b) Coarsening:

We require that coarsening occur only for 'siblings' descended from the same 'parent', this criterion means the mesh will return to its original topology when deformation is small. During coarsening sibling cells are destroyed and the original parent cell is returned. Nodes that exist in both the parent cell and in the siblings are assumed to undergo continuous motion and have their attributes copied from the associated sibling node. The mass of the parent cell's nodes are set to their original value.

#### IV. Current implementation

The current implementation of this technique is limited to two dimensional simulations. The simulation system and the adaptive techniques described can be extended, and this limitation resulted from the desire to establish the technique in a 'simpler' environment before tackling the slightly more difficult three dimensional simulations.

The program has been developed using C++ on a Sun Sparcstation 2 workstation with X11R4 graphics.

Simulation Type	Frame 50	Frame 75	Frame 100	Frame 125	Frame 150	Frame 175
Adaptive	73ms	85ms	76ms	76ms	127ms	178ms
Normal	1347ms	1348ms	1346ms	1347ms	1403ms	1437ms

Table 1: Comparison of Computation times for Adaptive and Normal simulations

Several dynamic data structures are used to store the nodes, cells and bonds associated with an object and links between these structures form the topological hierarchy as shown in Figure 4. The object also contains facilities for storing the 'family tree' associated with its cells and this is used during coarsening to restore the object to its original form.

In Figure 6 to Figure 9 several frames from a simulation of a solid ball hitting an elastic doughnut are shown. The doughnut is represented with a coarse uniform mesh so the effects of adaptive refinement and coarsening can be easily seen. In these frames the underlying bonds are shown to demonstrate the results of the adaptive refinement and coarsening. Figure 5 shows two frames from a different simulation that are fully rendered.



Figure 5: Two fully rendered frames

Table 1 gives a comparison of the computation times associated with this simulation and those of a non-adaptive model. Although the computation times for highly deformed states increase for the adaptive case, the time is greatly reduced compared to the non-adaptive method by concentrating calculations in regions of greatest deformation. In a larger model we expect the refinement to be concentrated in a small region and the time differences for the adaptive and non-adaptive methods will differ greatly.

Minor discrepancies in the compared simulations were also noted and these can be partly attributed to the node based collision response. During the initial deformation the forces acting on the ball are positioned differently in the two simulations because of the different node spacing. This results in a slightly different collision force. However, the resulting trajectory differences were minor and the addition of a more elaborate collision response system will reduce this effect further.

## V. Conclusions

The adaptive refinement and coarsening technique proposed shows great promise in providing optimised use of computational resources for physically based modeling. An h-type adaptation method is used to selectively refine the mesh used to model the object in areas where deformation is greatest. Additionally, refined areas that are no longer under deformation are coarsened to reduce the computational load. Suitable criteria for the selection of cells for refinement and coarsening have been described.

The results obtained from the two dimensional system have shown that the adaptive scheme is capable of achieving substantial reductions in computational complexity while maintaining a good approximation to model dynamics. Development is now under way to extend this system to three dimensions and to provide improved collision detection and response. We are also investigating the possibility of using the adaptive refinement and coarsening technique with a different physically based modeling system. It is hoped this system will be able to provide the interactive response demanded by surgical simulation systems.

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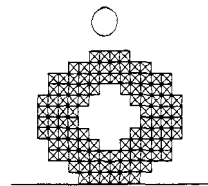


Figure 6: The start of the fracture simulation

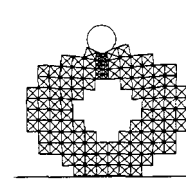


Figure 7: Deformation occurs and fracture begins

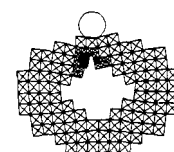


Figure 8: The fracture deepens and multiple levels of refinement occur

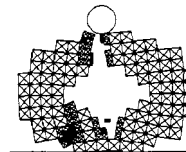


Figure 9: Coarsening occurs to reduce calculation times